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SIR JOSEPH LARMOR AND THE IONOSPHERE

SIR JOSEPH LARMOR MEMORIAL LECTURE

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I HAVE chosen the subject of "Sir Joseph Larmor and the Ionosphere" as the theme of this Memorial Lecture for two reasons. In the first place I think it is worth while to recall Sir Joseph Larmor's keen interest in the matter of the ionosphere, and also his timely intervention in the theoretical development of the subject in 1924 with a scientific paper which has proved of permanent value. In the second place I welcome an opportunity of paying a tribute to Larmor's friendly and encouraging interest in my own early work on the same topic.

I shall therefore be dealing largely with the five year period, 1919 to 1924, which immediately succeeded the end of the First World War, during which time Larmor and I were resident Fellows of St. John's College, Cambridge. Larmor was then senior and famous; I was a young don whose research career had been interrupted by war service almost before it had begun. As an undergraduate student before 1914 I had attended Larmor's lectures in the College, but I do not recall having had any conversation with him. But, after the war, I often sat next to him at the College High Table, and it must have been on some such occasion that he encouraged me to tell him something of what I was trying to do in the matter of research. Larmor was by no means a fluent conversationalist and spoke mostly in single sentences or even phrases. But he frequently helped a shy, younger, High Table companion with the opening remark: "And what have you been doing, to-day?" And I can well imagine that it was in reply to such a question that I was led to tell him what I was trying to do about the ionosphere.

However, to tell my story properly, I should begin it some twenty years earlier and say something of the way in which the question of the existence of the ionosphere had arisen in the first place. It was in the year 1901 that Marconi had succeeded in demonstrating the effective transmission of radio signals across the Atlantic Ocean, from Cornwall to Newfoundland. This was a great technical feat and naturally gave rise to much speculation concerning the use of radio in world communications.

But, to use Larmor's own words, it also "gave rise to a prompt query, from the late Lord Rayleigh, as to how the rays could manage to bend round the protuberance of the curved earth". The mathematical examination of the diffraction of radio waves round a conducting sphere was first carried out by H. M. Macdonald, and his first result indicated that diffractive bending alone could well account for Marconi's result. However, Lord Rayleigh questioned the accuracy of Macdonald's work on physical grounds. He pointed out that, if we reduce the linear scale of everything, the earth's radius and the wave-length of the radiation being correspondingly reduced, we can think of the radio problem as being similar to that of the bending of visible light round a copper sphere of a few centimetres radius. And, again to quote from Larmor, "familiar experience indicates that visible light could hardly creep to a sensible degree round the circumference of a sphere of that radius".

To his great credit, Macdonald returned to the mathematical problem of the diffraction of electric waves round a sphere, and the second time got the right answer. As a result of his calculations, and those of Poincaré, Nicholson, Watson and van der Pol, it became increasingly clear that the natural bending of waves round the earth was far too small to account for the steadily increasing ranges of communication which were being effected by means of wireless waves—ranges which eventually extended to the antipodes. It was thus evident that, in the formulation of their problems, the mathematicians had omitted to take into account some essential factor which favoured the long-distance travel of radio waves. Suggestions concerning the nature of such a factor were, fortunately, to hand; for, in 1902, both Kennelly and Heaviside had independently pointed out that, if the upper atmosphere were an electrical conductor, its influence would be to guide the radio waves round the protuberance of the earth's surface, energy being conserved between two concentric shells and not lost to outer space.

Heaviside's published reference to the possible influence of an electrically conducting stratum in the upper atmosphere is quite a brief one: it is contained in three sentences in his article on the Theory of Electric Telegraphy, in the third volume of the tenth edition of the *Encyclopaedia Britannica*, and is as follows:—

> "There may possibly be a sufficiently conducting layer in the upper air. If so, the waves will, so to speak, catch on to it, more or less. Then the guidance will be by the sea on the one side and the upper layer on the other".

These three sentences, however, do not express the whole result of Heaviside's consideration of the subject, for I have been informed by Dr. W. H. Eccles, a distinguished writer on the subject of the propagation of radio waves, that Heaviside developed his ideas further and submitted an article on his work to "The Electrician," for publication. But, alas, a referee, to whom it was submitted, did not consider it suitable for publication, and the article

never appeared in print. I may add that it may well have been that Heaviside's paper was not very easy to read and understand. Even the great Heinrich Hertz had had occasion to say to him, some years earlier : " You certainly are not aware how very difficult your papers are to others ". Some years ago I wrote myself to the Editor of " The Electrician " asking whether the old manuscript of Heaviside's still existed in the archives of his office. But, unfortunately, no trace of it could be found. This regrettable story has, however, one pleasant redeeming feature. Dr. Eccles, writing on the subject of the effect of an ionised layer on radio wave transmission in 1912, and knowing of Heaviside's further work on the subject and of the rejected article, decided to call the hypothetical conducting layer in the upper atmosphere the Heaviside Layer.

When I began to be interested in the subject of radio wave propagation, at the end of the First World War, there was much discussion concerning the existence—or non-existence—of the Heaviside Layer. There were some people who concluded that the intervention of an upper reflecting layer was not necessary to explain the favourable radio results, and that they could be accounted for by refractive bending of the waves in the lower atmosphere, due to the influence of a negative vertical gradient of water vapour. A German author, I remember, gave, as the summary of his paper on the subject, the single sentence: " Es gibt keine Heavisideschichte ".

I began my own work on radio propagation, at Cambridge, by examining the nature of radio signal fading. The initiation of broadcasting in Britain, in 1922, was a great help in these experiments ; for powerful and constant continuous-wave senders were in operation, over a greater part of the day, for the first time. Moreover the B.B.C. engineers generously provided extra transmissions on various occasions, often through the sunrise period, when other broadcasting stations were silent and interference was therefore at a minimum.

The earliest studies of signal variations made at Cambridge related to the emissions from the B.B.C. station in London. These observations showed that, whereas the signal strength at Cambridge was sensibly constant during the daytime, slight fading was experienced at night. A possible explanation was that such fading was due to interference effects between waves which had travelled straight along the ground, from sender to receiver, and waves which had travelled by an overhead route by way of reflection in the upper atmosphere.

We may picture such a state of affairs as is shown in Figure (1).

Here we see that radio waves can travel from the sender to the receiver by two paths—one direct and the other indirect. To explain the Cambridge results we must assume two things : first, that the reflected wave is only appreciable at night, and, second, that the nature of the reflection is variable in time. Corresponding results obtained for sending stations at greater distances than London indicated the increased importance of the night-time reflected wave as compared with the direct wave. For example, in

the case of continental broadcasting stations, only an extremely weak signal was received during the daytime; but, after sunset, the intensity, though variable, increased very greatly in magnitude. In terms of the Heaviside Layer theory this meant that the constant direct wave was weak by both day and night, and that the strong signals received after sunset were due practically entirely to waves which had taken the overhead path.

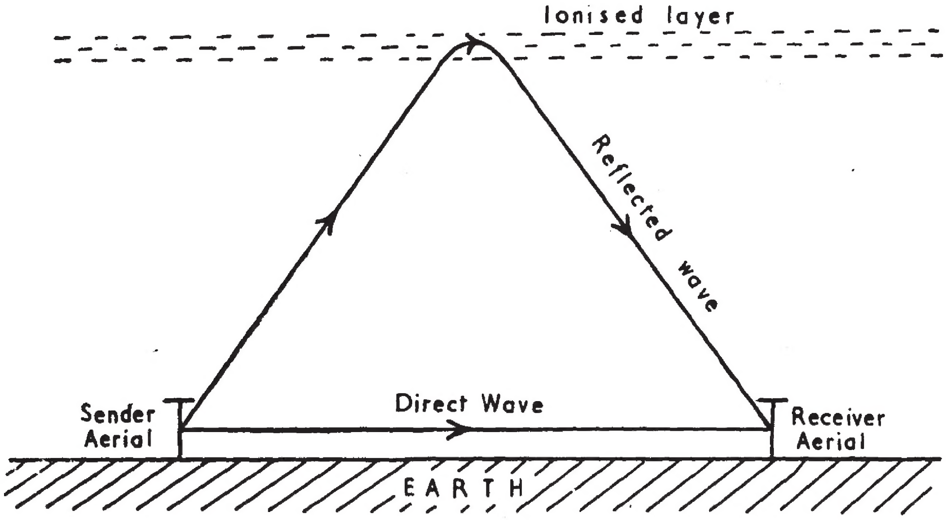

Fig. 1.—Illustrating transmission of radio waves from a sender to a receiver by two routes, one direct and the other indirect.

Such, then, was the kind of picture of things we had reached by, say, 1923. The Heaviside Layer theory gave a reasonably satisfying explanation of these simple studies of broadcasting transmissions in the medium wave band. But direct evidence of the existence of the layer, and any indication of its height above ground, were, of course, still lacking.

With the assistance of my first two research students, M. A. F. Barnett,[1] who was soon joined by J. A. Ratcliffe,[2] I tried to devise, and conduct, some experimental tests which would settle, one way or another, the controversy about the existence of the Heaviside Layer.

I well remember describing such of these plans as seemed most feasible in a note to Larmor. His knowledge of electro-magnetic theory, and especially of the work of Hertz, made him understand them at once, although the field of radio was, of course, not specially familiar to him. He returned the note with the added comment : " If you can do this it will help much. —J. L."

By the end of 1924 we had carried out our experiments and had located the Heaviside Layer at a height of about 90 Km. above the ground. I shall return to these results in a moment. But meanwhile Larmor's own

[1] Now Head of the New Zealand Meteorological Service.

[2] Now Director of Radio Research, Ditton Park, Slough.

interest in the theoretical problems involved had deepened and he had read such literature on the subject as was then available. His special concern was with the nature of the physical process by means of which the radio waves might be reflected, or refracted, by the hypothetical atmospheric stratum. Should one consider the ionised medium to act as a conductor or as a dielectric? By February 1924 he was lecturing on the theory of the subject to his advanced students, expounding to them his own results. In the early summer of that year there appeared the following examination question, due to Larmor, in a Schedule B paper in Part II of the Mathematical Tripos:—

> "Give a concise account of the principles of the transmission of free electric signals across space, with reference especially to atmospheric transmission over very long distances."

Sir John Cockcroft has told me that he attended Larmor's lectures during 1924 and was fortunate enough to hear the particular one devoted to the subject of radio transmission round the earth. As a result, he adds, he was able to answer Larmor's question on the subject in the Schedule B paper. It is pleasant for me to mention that the Cambridge Calendar shows that Sir John obtained a distinction in this examination!

In October 1924 Larmor read his well-known paper on the theory of the deviation of radio waves by an upper-atmospheric medium, entitled "Why Wireless Electric Rays can bend round the Earth". The paper was actually read to the Cambridge Philosophical Society, but it was published in the December 1924 issue of the Philosophical Magazine, Sir Oliver Lodge being its sponsor. Shortly after the paper was read at Cambridge, a short article by Larmor, with the same title and summarising his main results, appeared in "Nature" (1st November, 1924).

Larmor's concern, as I have mentioned earlier, was with the nature of the ionised medium, and with the fact that, in the process of reflection or refraction, very little attenuation of the waves must take place. Larmor's assumption that refraction, and not reflection, properly described the process of deviation turned out to be the correct one. He then went on to show that, if the process entails very little absorption, the medium must possess very small electrical conductivity, even if its refractive index is considerably modified. His central question therefore was: How could the medium bend the path of the waves without absorbing them at the same time?

To answer this question we must examine more closely the mechanism by which the waves are attenuated by the ionised medium. Under the influence of the alternating electric forces in the radio waves, the electrons or ions in the ionised medium are made to vibrate, and it is due to the additional radiation emanating from the vibrating particles that the process of wave travel is modified. But, unless the electrons or ions exist in a complete vacuum, they are constantly buffeted by the residual atoms and

molecules in the atmosphere. In this way their oscillatory motion is disturbed, or even destroyed. At the moment of impact the oscillating charged particle, having acquired its energy from the incident wave, possesses more than average energy and communicates some of this energy to the atmospheric atoms or molecules with which it collides. Energy is, in fact, communicated from the electric waves to the atmospheric gas by way of the oscillating electron or ion. We can say that the waves heat up the residual gases. This is the physical process of absorption.

Larmor's main conclusion was that, in order that this effect should be relatively small, one must picture the electron or ion as executing quite a number of vibrations, as a result of its stimulation by the incident electric waves, between a couple of successive impacts by the atmospheric gases. We may specify this quantitatively as follows. Let us suppose that the angular frequency of the waves is ω, and the collision frequency of the electrical carriers with the atmospheric molecules is ν; then Larmor showed that to produce substantial ray bending without marked attenuation, we must assume that ν^2 is small compared with ω^2. He further pointed out that, since the electrical conductivity of an ionised medium is, other things being equal, approximately proportional to ν, this means that its conductivity must be small. The medium behaves, in fact, like a very feebly-conducting dielectric which will refract waves without undue absorption.

Now, since our radio experiments on locating the Heaviside Layer by radio means were not performed till December, 1924, it will be seen that Larmor's theoretical discussions took place some months in advance of them. The experimental proof of the existence of the Heaviside Layer consisted of two parts, and may be most conveniently explained here in terms of Figure (1). As mentioned earlier, we may picture the radio waves as travelling from the sender to the receiver by two paths, one direct and the other indirect. Now, if there is a whole number of wave-lengths in the path difference between the ground and atmospheric ray paths, there will be a maximum of the composite radio signal intensity at the receiver; while if the path difference is equal to an odd number of half-wave-lengths a minimum of composite radio signal will be experienced. If now we suppose that the wave-length of the radiation emitted by the sender is continuously varied by a small amount, artificial fading will be produced, expressed as a regular succession of maxima and minima of composite signal strength. And if the number, n, of either is counted we can show that the path difference D should be given by the equation

$$D = n\,\frac{\lambda^2}{\triangle\lambda} \qquad \ldots\ldots \qquad (1)$$

Here λ is the mean wave-length, and $\triangle\lambda$ the small continuous change in wave-length deliberately made at the sender.

The first experiment of this type was carried out on an occasion shortly after midnight in December 1924, with the assistance of M. A. F. Barnett.

The B.B.C. sender at Bournemouth was used and the receiving station was established at Oxford. This experiment at once yielded evidence of a sequence of artificially produced maxima and minima of received signal intensity during the period of continuous wave-length change. By way of equation (1) the value of D could be estimated, from which the equivalent height of the reflecting stratum was found by simple triangulation. It came out to be about 90 Km.[3]

We were not, however, entirely satisfied with the results of this experiment since a sceptical critic could argue that all we had proved was the existence of transmission from sender to receiver by two paths of different length, and that both paths might have been situated near ground level. It was therefore necessary to prove that the longer path had, in fact, been pursued in an overhead fashion. In an entirely different set of experiments we therefore measured the angle at which the indirect train of waves came down to the ground at the receiver. This was done by comparing the simultaneous signal fading variations on two receivers, one with a loop aerial and one with a vertical antenna. These results indicated the reception of *downcoming* waves, and not waves reflected, say, from distant hills. Moreover the angle at which these waves reached the receiver indicated that they had been deviated in their overhead journey at about the same height as previously found.[4] The two sets of experimental results, we felt we could submit, were in accord with the Heaviside Layer theory, and, since we had now a method of identifying reflected waves, we could see a whole series of further investigations ahead of us.

The question of the publication of our results, however, arose. Mr. Barnett and I were, technically, workers in the Cavendish Laboratory, since I was a member of the teaching staff and he was a physics research student. After the paper was written I felt I should submit it to the Professor of Physics, Sir Ernest Rutherford, and seek his advice concerning possible publication. This I did, and was told that he would himself communicate it to the Royal Society. Upon mentioning this to Larmor the same evening, he replied, rather tartly, " Oh, no, I intend to communicate the paper myself ". Rutherford, with a kindly understanding, retired in the matter.

There is a postscript to this story. When we received the galley-proofs of our article from the Royal Society, we found that Larmor had given it a different title. I cannot remember now exactly how we had headed the paper in the first instance, but I can well imagine that the title contained some reference to the Heaviside Layer. However Larmor had written, instead : " On Some Direct Evidence for Downward Atmospheric Reflection of Electric Rays ". You will notice here, as elsewhere, Larmor's preference

[3] I have described this experiment in terms of the phraseology and nomenclature we actually used at the time. But nowadays we should say that the Heaviside Layer was first located by the method of radar, using frequency-modulation.

[4] Mr. Barnett and I were greatly assisted, in these experiments on the comparison of signal fading in receivers with loop and vertical antennae, by Mr. J. A. Ratcliffe.

for the word " ray ". Throughout his own 1924 paper he stresses the analogy of radio with optical phenomena ; and, indeed, this was a useful hint, for the development of much radio theory has been greatly assisted by reference to corresponding optical treatments already available.

I feel quite sure that it was Larmor's own work which suggested to me that the effective electrical particles in the Heaviside Layer were really free electrons and not molecular ions. It is true that he himself had left the matter not entirely decided, since he frequently used the phrase " electrons or light ions". But he had stressed the fact that the air pressure at the atmospheric level of the layer must be very low ; and laboratory experiments had already suggested that free electrons formed part of the population of the negative charges in a gas discharge at low pressures.

However it turned out that there were methods of settling the matter, by further radio experiments, in which not only the mass of the effective ionospheric particle could be determined, but also the electrical sign—positive or negative—of its charge. These methods emerged in the following way. In a paper I read at a Physical Society Symposium on the condition of the upper atmosphere, in November 1924, I pointed out that the whole theory of electric wave propagation in an ionised medium would have to be considerably modified if the effective ionospheric particles were, in fact, of electronic mass, because of the influence of the earth's magnetic field. I remember mentioning the same point to Larmor before he published his own paper. His reply was that he had overlooked the matter entirely ; and, because of this, he did not feel he should modify his own draft. He generously suggested that it was for me to take over the development of the new theory as a project of my own.[5]

The restatement of the theory of the propagation of waves in an ionised medium under the influence of an imposed magnetic field turned out to be complicated rather than difficult, since the essential physics of the matter was not in doubt. However, the development of the magneto-ionic theory, as it is now called, did emphasise the fact that the earth's magnetic field was of sufficient magnitude to exert a profound effect on both the refractive index and absorption coefficient of an ionised layer, especially for the radio wave-lengths we were then using in the direct examination of that stratum.

As an illustration of the magnitude of the effect of the earth's magnetic field I may quote results applying to the case when the waves travel along the direction of the magnetic force. In such a case the equation for the refractive index n, which, without a magnetic field, is

$$n^2 = 1 - \frac{4\pi N e^2}{m\omega^2} \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

[5] Larmor did, however, start introducing the magneto-ionic theory in his class lectures, confining his treatment, as S. Goldstein has recorded, to cases of propagation along, and at right angles to, the magnetic field.

becomes

$$n^2 = 1 - \frac{4\pi N e^2}{m\left(\omega^2 \pm \dfrac{eH}{mc}\,\omega\right)} \quad . \quad . \quad . \quad . \quad (3)$$

In equation (3), H is the magnitude of the earth's magnetic field ; and taking its value as 0·45 gauss it is easy to show that the term $\left(\dfrac{eH}{mc}\right)$ is numerically of the same order as ω, for the medium wave band of 200 to 600 metres. Moreover, as equation (3) indicates, there are two possible values for the refractive index ; and the theory shows that these are associated with two components of equal and opposite circular polarisations. If we assume that the value of e is negative, as in the case of electrons, we can write (3) more explicitly as follows:—

$$n^2 = 1 - \frac{4\pi N e^2}{m\,(\omega^2 + \omega\omega_H)} \quad . \quad . \quad . \quad \text{(left-handed circularly polarised ray)} \quad . \quad . \quad (3a)$$

and

$$n^2 = 1 - \frac{4\pi N e^2}{m\,(\omega^2 - \omega\omega_H)} \quad . \quad . \quad . \quad \text{(right-handed circularly polarised ray)} \quad . \quad . \quad (3b)$$

where

$$\omega_H = \frac{|\,e\,|\,H}{mc} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Moreover the same more complete theory shows that these two oppositely circularly polarised components experience different absorptions, due to the effect of the collisional friction experienced by the electrons. Using the customary notation, and taking (3a) as referring to the ordinary ray and (3b) to the extra-ordinary ray, it can be shown that

$$\frac{K\ \text{(extra-ordinary ray)}}{K\ \text{(ordinary ray)}} = \left(\frac{\omega + \omega_H}{\omega - \omega_H}\right)^2 \quad . \quad . \quad . \quad (5)$$

In other words, for propagation of medium waves along the direction of the magnetic field there is differential absorption of the two circularly polarised components which travel, the right-handed component being more heavily absorbed than the left-handed component. This effect is naturally reversed if the waves travel in a direction opposed to the direction of the imposed magnetic field ; while, of course, both effects would be reversed again if the electron had a positive charge!

The above theory was checked in an experimental fashion, by Mr. J. A. Ratcliffe and myself in the years 1927–28, when we measured the state of polarisation of waves deviated by the Heaviside Layer. For waves of the order of 300 to 400 metres we found that the downcoming waves were approximately circularly polarised with a left-handed sense of rotation. The observations were made at Peterborough, and, since it was known that the waves originally emitted by the sending stations (emitters at both

Teddington and Birmingham were used) were of linear polarisation, it was evident that the conversion to left-handed circular polarisation had been effected within the ionised layer during the process of refraction. Our tentative explanation of this result was that, since the downcoming waves were travelling approximately along the lines of the earth's magnetic field during the last part of their journey in the layer, the left-handed circularly polarised component (ordinary ray) was predominant, due to the practical extinction of the right-handed component (extra-ordinary ray) by absorption. But, as Mr. Ratcliffe and I went on to point out, the best check of such an explanation would be to repeat the experiment in the southern hemisphere, where the magnetic field would be reversed, and where the resultant polarisation should therefore be right-handed.

The Australian Radio Research Board, on its formation in 1929, offered to make facilities for the necessary polarisation measurements available, and these were entrusted to Mr. A. L. Green, another research student of mine, who had been associated with the original observations at Peterborough. Working in New South Wales, under conditions which were ideal for the strict comparison of results in the two hemispheres, Mr. Green found that, in the southern hemisphere, downcoming waves in the medium wave band were approximately circularly polarised with a *right-handed* sense of rotation.

This Australian result, we now all felt, left no room for doubt about the general correctness of the magneto-ionic theory; and, that now being accepted, the results further indicated that the effective particles in the absorbing stratum, whatever their mass might be, possessed negative charges. But, technically, there still remained the further step of trying to decide between negative electrons or negative light ions, though the fact that there was strong differential absorption in the frequency range of 1 to 2 Mc/s. pointed strongly to electrons.

Now the experimental proof of the existence of the Heaviside Layer had emerged from oblique-incidence radio experiments. But we soon found that we could improve our technique so as to permit the study of reflected radio waves incident normally on the reflecting stratum. This greatly simplified the interpretation of the results, in that we could assume that the waves were reflected under conditions when the refractive index of the medium had just been reduced to zero. In addition to measuring heights of reflection by the frequency-modulation method, we started to use the elegant pulse-modulation technique of measuring the same quantity, which Breit and Tuve had invented in 1925. In its application in England we used cathode-ray tube delineation of the ground pulse and of the subsequent echo pulses. And it was with apparatus of this kind that Dr. G. Builder and I discovered the magneto-ionic splitting of echoes. Studying reflection from the upper atmospheric ionised layer, which I had found to exist at a higher level than the Heaviside Layer, we found that a single incident radio pulse was reflected as a doublet. And at once we were led to associate this splitting with the doubly-refracting properties of the ionosphere, for

it seemed that the new phenomenon exhibited such properties in the most graphic form. Such a view was strengthened when the polarisations of the separate components of the doublet were determined, for it was found, as theory predicted, that they were both circularly polarised but in opposite sense.

By making observations on waves reflected from the upper layer, Dr. Builder and I found that the difference in the heights of reflection of the two components increased as the radio frequency employed was increased. This is illustrated in Figure (2) where equivalent height of reflection is plotted as a function of radio wave frequency.

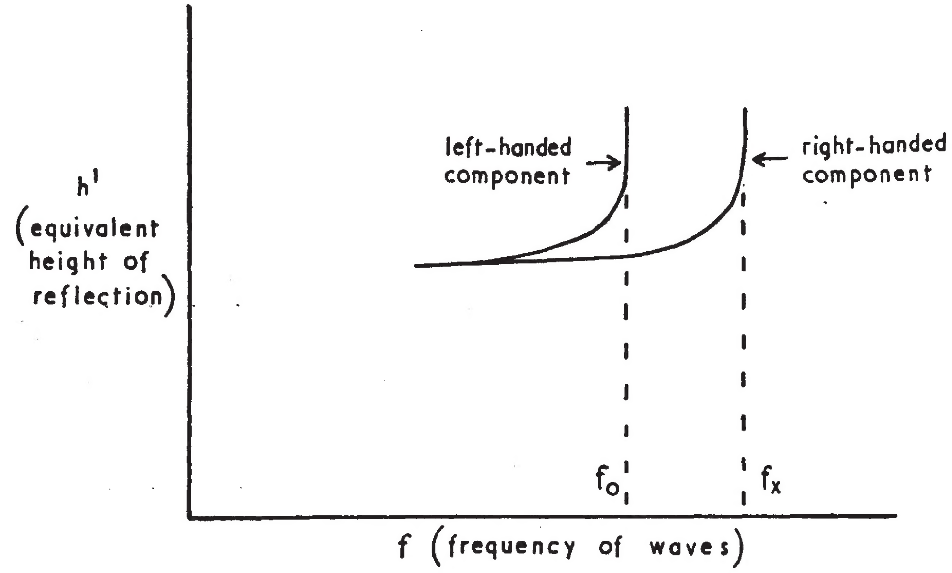

FIG. 2.—Showing the relation between equivalent height of ionosphere reflection and radio wave frequency under conditions of ionospheric penetration. The magneto-ionic double refraction is to be noted.

Moreover it was found that the component which was returned as the left-handed ordinary ray penetrated the layer at a lower frequency than the right-handed extra-ordinary ray; and the difference between the two penetration frequencies (f_x and f_0) was found to be very approximately constant.

Now I had already shown that, according to the magneto-ionic theory, the refractive index of an ionised medium became reduced to zero, permitting the reflection of radio waves at vertical incidence, when

$$N = \frac{\pi e^2}{m} f^2 \text{ (ordinary wave)} \quad \dots\dots\dots\dots \quad (7)$$

and

$$N = \frac{\pi e^2}{m} (f^2 - f f_H) \text{ (extra-ordinary wave)} \quad \dots\dots \quad (8)$$

where f is the radio wave frequency while f_H is the gyro-frequency with

which electrons, when moving freely, spiral round the lines of the earth's total magnetic force. If now we are dealing with critical penetration conditions, N is equal to N_m, the maximum electron density of the layer, and we write

$$N_m = \frac{\pi e^2}{m} f_0^2 \quad . \quad . \quad . \quad . \qquad (9)$$

and

$$N_m = \frac{\pi e^2}{m} (f_x^2 - f_x f_H) \quad . \quad . \quad . \qquad (10)$$

So that

$$f_0^2 = f_X^2 - f_X f_H$$

or

$$f_H = \frac{f_X^2 - f_0^2}{f_X} \doteqdot 2 (f_X - f_0) \quad . \quad . \quad . \quad . \qquad (11)$$

Now f_H is equal to $\dfrac{eH}{2\pi mc}$ so that, in e.m. units throughout,

$$\frac{e}{m} \doteqdot \frac{4\pi}{H} (f_e - f_0) \quad . \quad . \quad . \quad . \qquad (12)$$

Now $(f_e - f_0)$ was experimentally observed to be about 0·65 Mc/s. so that since $H = 0{\cdot}45$ gauss, we find

$$\frac{e}{m} = 1{\cdot}6 \times 10^7 \text{ e.m.u.,} \quad . \quad . \quad . \quad . \qquad (13)$$

which compares with the usually accepted value of $1{\cdot}7 \times 10^7$ e.m.u. for electrons. In other words, by radio experiments alone it was possible to show that the effective electrical carriers in the ionosphere possessed a negative charge, and that the "charge to mass ratio" of those carriers was that characteristic of the electron itself.

Well, there is the story of those early years in the history of ionospheric investigation. It has, naturally, been most pleasant for me to have an occasion to recall its main incidents. No one would, of course, claim that Larmor's contributions to the study of the ionosphere equal in importance his other weighty contributions to mathematical physics. But I like to think that he found the study of the ionosphere a congenial one—not only in itself, but also perhaps because it brought him into contact with younger people. To many people in Cambridge, Larmor appeared as an aloof and remote figure. Perhaps his own generation tended to be awed by his great reputation. But to us younger folk he was friendly, considerate and generous in the attention he gave to us, and our association with him will always remain a proud and fragrant memory.